sensing an AC magnetic field radiated from a magnetic field source associated with the digging head by an above-ground magnetic sensor, and

calculating at least one of the positions of the magnetic field source from the magnitude and direction of the sensed magnetic field, at least one of the positions of said magnetic field source, the tilt angle of said magnetic field source to the vertical direction and the azimuth of said magnetic field source that is its axial direction in a horizontal plane being calculated by using a signal magnetic field component obtained from the synchronous detection of an original sensed magnetic field by using a projective component of said magnetic field as a reference signal.

REMARKS

This Amendment is responsive to the Office Action mailed November 10, 2003. The Examiner's comments in the Office Action have been considered.

Claims 1-25 are rejected and the specification is objected to. The Examiner has requested that a Substitute Specification be filed. Submitted herewith is a marked-up copy of the substitute specification indicating all additions and deletions made to the original specification. Also submitted is a clean copy of the specification as amended, without indication of revisions. The Substitute Specification has been revised to respond to the Examiner's objections and to correct all uncovered idiomatic, typographical and grammatical errors. No new matter has been added.

Claims 1-25 have been objected to as being indefinite for failing to particularly point out and distinct claim the subject matter that applicant regards as the invention. Claim 1 has been amended to address this rejection, and the claim has, effectively, been divided into two independent claims: amended claim 1 and new claim 26. This eliminates, for example, alternate

expressions, and other revisions have been made to eliminate those problems with idiomatic English of which applicant is aware. Insofar as the Examiner's query "What does calculating the position of the magnetic field source have to do with the noise magnetic field?", it is respectfully submitted that the larger part of the specification discusses this very issue. The position of the magnetic source is calculated as a function of or in the presence of a noise magnetic field, and it is this method of calculating the positions of the magnetic field sources in the presence of noise magnetic fields that is the crux or essence of the subject invention. The relationship has been clarified in the amended claims as well as from the description as a whole.

Claim 1-25 are rejected as being fully anticipated by U.S. Patent No. 6,411,094 issued to Gard et al. Making this rejection, the Examiner merely states that Gard discloses a system and method for measuring the magnetic field of a boring device that takes into account for underground power lines. Insofar as the subject claims are understood, the Examiner concludes that Gard et al. anticipates all of them. The Examiner's full anticipation rejection on the basis of Gard et al. is respectfully traversed, and it is respectfully requested that this rejection be reconsidered and withdrawn in light of the amendments to the claims as well as the discussion that follows.

The present invention relates to a method for obtaining a part of a magnetic field radiated from a probe (e.g., digging head 2 in Fig. 1(A)) when magnetic fields, mixed or appearing simultaneously with magnetic fields issued by the probe as well as by power lines and/or other sources of electro-magnetic radiation that can provide disturbances and cause inaccuracies in the region of the probe.

In the present invention, the method as defined in claim 1 utilizes a projective component of the magnetic field projected on a straight body orthogonal to a vector-valued direction of the noise magnetic field. Thus, in the present invention, "projection" means "to project a measured magnetic field to a plane perpendicular to the magnetic field radiated from those sources other than the probe," so that the magnetic field radiated from the probe is obtained in separation from a magnetic field created by the probe. In the present invention all the magnetic fields from the probe and the other magnetic fields are detected by a receiver positioned over the ground surface.

The Gard et al. patent, in contrast, provides no means for separating a signal emitted from the beacon 220 from a magnetic field radiated from an object, such as a power line. (See column 5, line 25.) In the reference, the position of the beacon 220 is detected with respect to the object 402 (assumed by a linear body through which a current is flowing or flows from the signal generator 404) under a condition where the magnetic field emitted from the object 402 is already separated – or where only the magnetic field emitted from the 402 is detected by the sensor (see sensor assembly components described in column 6, line 28, through column 7, line 8). In the reference, therefore, "projection" means that the magnetic field detected by the sensor assembly 218 is reformed to another standard coordinate by the use of the pitch angle φ and the roll angle γ (see column 7, lines 64-73) detected by the same sensor assembly 218. In the construction, the signal radiated from the beacon 220 is detected by the tracker 228, while the magnetic fields radiated from those other than the beacon 220 are detected by the detection module 218. The magnetic field is assumed to be a linear body, while the reference proposes to detect the object. In the present invention, all the magnetic fields from the probe (corresponding to the beacon 220)

and the other magnetic fields are detected by a receiver (corresponding to the tracker 228) positioned over the ground surface. In the reference, the magnetic field generated is assumed as a linear body, and the reference proposes to detect the object. Further, the detection module 218 in the reference determines the magnetic field characteristic for the distortion of the earth's magnetic field that is produced by an underground magnetic object. The total magnetic field is determined and compared to a reference value for the earth's magnetic field.

In view of the above, it is submitted that the present invention, as now defined in claims 1 and 26, clearly and patentably distinguishes over the teachings in Gard et al., because the method disclosed in Gard et al. does not teach making a calculation with respect to the magnetic field source by using a projective component of the magnetic field, sensed by the magnetic sensor on a straight body orthogonal to a vector-valued direction of the noise magnetic field.

This application appears to overcome the rejections and objections raised by the Examiner and distinguishes over the applied art. Early allowance and issuance of this application is accordingly and respectfully solicited.

Applicant hereby petitions that any and all extensions of time of the term necessary to render this response timely be granted. COSTS FOR SUCH EXTENSION(S) AND/OR ANY OTHER FEE DUE WITH THIS FEE DUE WITH THIS PAPER THAT ARE NOT FULLY COVERED BY AN ENCLOSED CHECK MAY BE CHARGED TO DEPOSIT ACCOUNT #10-0100.

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SUBSTITUTE SPECIFICATION
(marked-up version)

BACKGROUND OF THE INVENTION

[Technical Field of the Invention]

Field of the Invention.

The present invention relates to a method [for] of determining the digging position of a digging head in a [non-open-cut method of] substantially horizontal digging or excavation and, more particularly, to a method [which] that ensures accuracy in determining positions of the digging head by lessening the influence of [a] noise magnetic field [of] frequency components close to [that of] the signal magnetic field to be measured.

[Prior Art]

Brief Description of the Prior Art.

A horizontal drilling method, which is one of the [non-open-cut] boring or trenching methods of this kind, uses a small-diameter pipe of 100 mm or less [across] for horizontally digging in the ground, and _,_ accordingly, [such a] the kind of precision position_-_determining apparatus [as] used in an ordinary small-diameter driving method of excavation cannot be placed near a drill. To solve this problem, it is customary in the art to generate [adopt a method in which] an AC magnetic field [is generated] by means of a coil mounted in the drill head that is [and] detected by an above-ground magnetic sensor like a coil to determine the current digging position.

This method is simple and easy, but since the magnetic field by the coil is a [dipole] dipolar magnetic field, [it] the field rapidly attenuates with distance from the coil. [Hence, this] The method is defected in that it is unable to [has a defect of inability to] achieve a highly reliable [high-reliability] determination of the digging position when a power line or similar magnetic noise source is present in [the vicinity of] or around the place where [to perform] the position determination is performed.

[SUMMAR] SUMMARY OF THE INVENTION

An object of the present invention is to provide a position_-_determination

method that permits [high-reliability] highly reliable determination of the digging position by detecting [on the ground] the AC signal magnetic field [provided] from a coil housed in [the] a drill head even if [a] another noise magnetic field is present [which] that [affects the position] might have an effect on the determination of the digging position .

To attain the above object, a [digging position determining] method for determining digging position, for a boring or trenching excavation, according to the present invention [for non-open-cut excavation], which (1) senses an AC magnetic field [provided] from a magnetic field source by means of a magnetic sensor provided on the ground and (2) calculates the position of the magnetic field source from the magnitude and direction of the [sensed] magnetic field that is sensed [, said] . This method's [method having a] construction is characterized [in that] by several features.

In [case] situations where there is, in addition to [a] the signal magnetic field generated by [said] the magnetic field source, [there exists a] another noise magnetic field generated by a nearby current, at [lease] least one of the [position] positions of said magnetic field source -- the tilt angle of said magnetic field source to the vertical direction and the azimuth angle of its axial direction of said magnetic field source in a horizontal plane -- is calculated [,] from a [projective] projecting component of the magnetic field sensed by [said] the magnetic sensor and projected on a plane or straight line orthogonal to a vector-valued direction of [said] the noise magnetic field.

In this regard, it is useful to review the [That is, in 1999 year's] investigation and research relating to useful utilization techniques of energy resources [:] entitled ["Research for low-loss energizing techniques in establishment of advanced telecommunication network",(executed by] "Research for Low-Loss Energizing Techniques in Establishment of Advanced Telecommunications Networks" (the Composite Development System for New Energy Industrial Technique). Here, [it is described that] external noise magnetic fields, which [affects] affect the

[position] determination of position in a boring or trenching [in the non-open-cut] method of excavation, [is mostly] are determined to be primarily generated by a current of some kind. In this case, the magnitude of the noise magnetic field varies irregularly with time, but its vector-valued direction is constant at each field -sensing position.

The present invention attains its object through the adoption of the following steps: [(A) and (B).]

(A) The direction of the noise magnetic field is detected, and a sensed magnetic field in which the noise magnetic field and a signal magnetic field are mixed is projected on a plane or straight line orthogonal to the direction of the noise magnetic field to obtain a projective component.

Since the projective component is theoretically free from a component derived from the noise magnetic field, at lease one of the position, azimuth angle and tilt angle of the magnetic field source is calculated so that the magnitude of the projective component (in the case of projection on the straight line) or it magnitude and direction (in the case of projection on the plane) is substantially equal to a theoretically calculated value of a corresponding quantity of a magnetic field generated from a magnetic field source, or ,has a minimum difference between the former and the latter. The sensed magnetic field is obtained by sensing magnetic fields at different positions whose number is determined by how many ones of the position, azimuth angle and tilt angle of the magnetic field source are unknowns and how such unknowns are calculated.

(B) To obtain the noise magnetic field [,] (1) when the number of noise magnetic fields is virtually "1",

[a) When the number of noise magnetic fields is virtually one:

·] The noise magnetic field is sensed to obtain its direction essentially in the absence of a signal magnetic field [.] ; or,

[·] When the noise magnetic field has frequency components at frequencies different from that of the signal magnetic field, the frequency components are

measured to obtain the direction of the noise magnetic field.

[b)] (2) When the number of magnetic fields is virtually [two:] "2", the [The] frequency components of a first one of the two noise magnetic fields, which are widely spaced from the frequency components of the second noise magnetic field and the signal magnetic field, are measured to obtain [a] the vector direction of the first noise magnetic field, and the frequency components of the second noise magnetic field, which are widely spaced from the frequency components of the first noise magnetic field and the signal magnetic field, are measured to obtain [a] the vector direction of the second noise magnetic field.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the present invention will be clearly understood from the following description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a perspective view [explanatory of] that shows the placement of a magnetic sensor in the method of the present invention [method];

Fig. 2 is a vector diagram [explanatory of] showing the principle of measurement according to the method of the present invention [method in a case of] where there is one noise magnetic field source;

Fig. 3 is a vector diagram [explanatory of] showing the principle of measurement according to the method of the present invention [method in a case of] where there are two noise magnetic field sources;

Fig. 4 is a flowchart illustrating a procedure for obtaining a projective component according to the method of the present invention [method in a case of] where there is one noise magnetic field source;

Fig. 5 is a flowchart illustrating a procedure for obtaining a projective component according to the method of the present invention [method in a case of] where there are two noise magnetic field sources;

Fig. 6 is a flowchart illustrating a procedure for obtaining a signal magnetic field [in a case of] where there is one noise magnetic field;

Fig. 7 is a flowchart illustrating a procedure for obtaining a signal magnetic field [in a case of] where there are two noise magnetic fields;

Fig. 8 is a flowchart showing a measurement procedure [in] according to the method of the present invention [method];

Fig. 9 is a flowchart showing a procedure for calculating the position of [the] a signal magnetic field according to the method of the present invention [method in a case of] where there is one noise magnetic field [when] and where the number of unknowns and the number of equations are the same [as to each other];

Fig. 10 is a flowchart showing a procedure for calculating the position of [the] a signal magnetic field source according to the method of the present invention [method in a case of] where there is one noise magnetic field source [when] and where the number of equations is [larger] greater than the number of unknowns;

Fig. 11 is a flowchart showing a procedure for calculating the position of [the] a signal magnetic field according to the method of the present invention [method in a case of] where there are two noise magnetic field sources [when] and where the number of unknowns and the number of equations are the same [as to each other];

Fig. 12 is a flowchart showing the procedure for calculating the position of [the] a signal magnetic field source according to the method of the present invention [method in a case of] where there are two noise magnetic field sources [when] and where the number of equations is [larger] greater than the number of unknowns;

Fig. 13 is a flowchart showing an example of a procedure for obtaining [the] a signal magnetic field [through the use of] by using the magnitude of the signal magnetic field vector;

Fig. 14 is a flowchart showing another example of a procedure for obtaining [the] a signal magnetic field [through the use of] by using the magnitude of the signal magnetic field vector;

Fig. 15 is a perspective view [explanatory of] showing the placement of a magnetic sensor for determining the direction of a noise magnetic field according to the method of the present invention [method] when [a] the digging head [, which] is [a] the signal magnetic field source [,] and is distant from the position of measurement;

Fig. 16 is a flowchart showing a procedure for calculating the direction of [the] a noise magnetic field according to the method of the present invention [method in a case] where the digging head is [distance] distant from the position of measurement and the signal magnetic field source stops to generate the magnetic field; [stops generating a magnetic field??????]

Fig. 17 is a flowchart showing a procedure for calculating the direction of [the] a noise magnetic field according to the method of the present invention [method] when the signal magnetic field and the noise magnetic field [are mixed to] mix with each other;

Fig. 18 is a signal frequency spectrum diagram showing [explanatory of] how the [operation of selecting] selection of a frequency for maximizing a frequency spectrum is used in the process [for] of calculating the direction of the noise magnetic field in the flowchart as shown in Fig. 13;

Fig. 19 is a flowchart [explanatory of] showing a first method [by which] for using the flow of candidate vector calculating process [is used] in the process [for] of calculating the direction of the noise magnetic field in the flowchart as shown in Fig. 17;

Fig. 20 is a flowchart [explanatory of] showing a second method [by which] for using the flow of candidate vector calculating process [is used] in the process [for] of calculating the direction of the noise magnetic field in the flowchart as shown in Fig. 17;

Fig. 21 is a flowchart [explanatory of] showing a method [by which] for using the flow of process [for] of evaluating the candidate vector and obtaining the direction of the noise magnetic field [is used] in the process [for] of calculating the

direction of the noise magnetic field in the flowchart as shown in Fig. 17;

Fig. 22 is a signal frequency spectrum diagram [explanatory of] showing how the [operation of selecting] selection of a frequency for maximizing a frequency spectrum is used in the process [for] of calculating the direction of the noise magnetic field in the flowchart as shown in Fig. 13.

Fig. 23 is a signal waveform diagram [explanatory of] showing the [operation] role of specifying a period in which only [a] one noise magnetic field exists [through utilization of a] by using the fact that the amplitude of the sensed magnetic field signal [becomes small] diminishes during the OFF period of the signal magnetic field that is turned OFF by a predetermined procedure, in the [calculation of] process of calculating the direction of the noise magnetic field according to the method of the present invention [method];

Fig. 24 is a signal waveform diagram showing the role of instantaneous variations in the amplitude of the sensed magnetic field signal when the signal magnetic field is periodically turned OFF in the calculation of the direction of the noise magnetic field according to the method of the present invention [method];

Fig. 25 is a signal waveform diagram showing the role of instantaneous variations in the amplitude of the sensed magnetic field signal when the signal magnetic field is randomly turned OFF in the calculation of the direction of the noise magnetic field according to the method of the present invention [method];

Fig. 26 is a flowchart showing a method for calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, a period during which a particular magnetic field is OFF [is] being specified by a sequence [starting at the time] that starts when a correlation function between the sequence and the sensed magnetic field [becomes] is at its maximum, and the direction of the sensed magnetic field in the specified period is regarded as the direction of the noise magnetic field;

Fig. 27 is a flowchart showing a method [for] of calculating the direction of

the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, and the starting time of a sequence indicating the most likely ON/OFF state of the signal magnetic field is calculated from a plurality of times when a correlation function between the predetermined sequence and the sensed magnetic field [becomes] <u>is at</u> <u>its</u> maximum;

Fig. 28 is a flowchart showing the method [for] <u>of</u> calculating [he] <u>the</u> direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, <u>where</u> the correlation function between the predetermined sequence and the sensed magnetic field is calculated at each of a plurality of time points at which the period of the sequence is equally divided [,] <u>and</u> the magnetic field is projected at each [time] point <u>in time</u> to a vector formed by the calculated function, and one of vectors whose [variance] <u>variation</u> is [minimum] <u>minimal</u> is regarded as the direction of the noise magnetic field;

Fig. 29 is a flowchart showing another method for calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, <u>where</u> a correlation function between the predetermined sequence and the sensed magnetic field is calculated at each of a plurality of time points at which the period of the sequence is equally divided, the magnetic field is projected at each time point to a vector formed by the calculated function, and one of vectors whose [variance] <u>variation</u> is [minimum] <u>minimal</u> is regarded as the direction of the noise magnetic field;

Fig. 30 is a flowchart showing [the] <u>a</u> method [for] <u>of</u> calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, and the starting time of a sequence indicating the most likely ON/OFF state of the signal magnetic field is calculated from a plurality of [time] points <u>in time</u> when

the correlation function between the predetermined sequence and the sensed magnetic field [becomes] is at its maximum;

Fig. 31 is a flowchart showing [still] yet another method [for] of calculating the direction of the noise magnetic field according to the present invention in which the signal magnetic field is turned OFF on the basis of a predetermined sequence, a correlation function between the predetermined sequence and the sensed magnetic field is calculated at each of a plurality of [time] points in time into which the period of the sequence is equally divided, the magnetic field is projected at each [time] point in time to a vector formed by the calculated function, and one of the vectors whose [variance] variation is [minimum] minimal is regarded as the direction of the noise magnetic field; and

Fig. 32 is a perspective view depicting an example of a magnetic field sensing frame for use in the present invention.

DETAILED DESCRIPTION OF THE INVENTION

As depicted in Fig. 1, [in a case where] the position of a digging head 2 under the ground surface 1, which [is] creates a signal magnetic field source to be sensed, is determined using a magnetic sensor 4 placed on the ground surface 1 at a proper position [when] at the same time that a power line or similar magnetic noise source 3, which generates a noise magnetic field, is placed near the digging position to be determined [, there are present] . More specifically, a signal magnetic field vector H_s is provided from the digging head 2 and a noise magnetic field vector H_n is provided from the magnetic noise source 3, such as power line. In this case, the magnetic sensor 4 senses a resulting vector H_m that is a combined version of the signal magnetic field vector H_s and the noise magnetic field vector H_n.

Referring to Fig. 2, a [Now, let the] noise magnetic field of a position vector r and at time t [be] is identified as a vector $H_n(r, t)$. On the other hand, [let] the signal magnetic field generated by magnetic [filed] field generating means for position sensing [be] is identified as [a] the vector $H_s(r-r_c, \theta_c, t)$. Here [,] the

vector θ_c is [an] the angle of orientation of the magnetic field generating means, which is defined by three angles of rotation in the coordinate system fixed to the ground that is the coordinate system fixed to the magnetic field generating means. ????????

[Since] Because the noise magnetic field and the signal magnetic field are [both] sensed simultaneously, and [since] because the noise magnetic field vector H_n([t] r, t) varies randomly with time, it is [impossible] only possible to extract [only] the signal magnetic field vector $H_s(r-r_c, \theta_c, t)$ from the measured magnetic field vector $H_m(r-r_e, \theta_c, t)$ [unless] if the statistical properties of the noise magnetic field are known and the noise magnetic field is signal-wise orthogonal to the signal magnetic field. And even [Even] if the statistical properties [for] separating the noise magnetic field from the signal magnetic field are known [prior to the determination of the] determining the latter's position [of the latter], [the] this separation [calls for] comprises a large amount of data, and [hence] therefore the conventional scheme is [not ever] never practical.

According to the present invention, the direction of a vector $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ is obtained by separated means [,] and in a coordinate system shown in Fig. 2, where a component vector $H_m^P(r-r_c, \theta_c, t)$, is projected to a plane vertical to the direction of a vector $e_n(r)$ of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$, as shown in Fig. 4 (S1, S2, S3).

$$\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)=\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)-(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot\mathbf{e}_n(\mathbf{r}))\mathbf{e}_n(\mathbf{r}). \quad (1)$$

This component does not contain the noise magnetic field for the reason given below. Since

$$\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)=\mathbf{H}_s(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)+\mathbf{H}_n(\mathbf{r},\ t)=\mathbf{H}_s(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)+|\mathbf{H}_n(\mathbf{r},\ t)|\mathbf{e}_n(\mathbf{r}). \quad (2)$$

it follows that

$$\mathbf{H}_{\mathrm{m}}{}^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)=\mathbf{H}_{\mathrm{s}}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)-(\mathbf{H}_{\mathrm{s}}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\cdot\mathbf{e}_{\mathrm{n}}(\mathbf{r}))\mathbf{e}_{\mathrm{n}}(\mathbf{r}). \qquad (3)$$

from which it can be seen that the projective component vector $H_m{}^P(r-r_c, \theta_c, t)$ does not contain the component of the noise magnetic field vector $H_n(r, t)$.

However, the projective component vector $H_m{}^P(r-r_c, \theta_c, t)$ has lost information of one axis by the projection on a plane [vertical] normal to the direction of the vector $e_n(r)$. That is, since the same projective components are obtained [irrespective] regardless of the magnitude of a component parallel to the vector $e_n(r)$, two independent components are obtained.

Although any method can be used to obtain the two independent components [;] , it is possible to use [such a] the method [as] described below.

That [one of] coordinate axis [axes] of a measurement coordinate system C_M ([which will be] described [later on] below) [, which] that is not parallel to the direction $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ [,] is chosen. [Let a] A unit vector in the direction of the chosen coordinate axis [by] is identified as [a] vector e_m. A vector product, $e_{p,1}=e_m \times e_n(r)$, of the unit vector and the direction $e_n(r)$ is perpendicular to the direction of the vector $e_n(r)$ [,] and hence [it is] contained in the plane of projection and [is] perpendicular to the coordinate axis e_m. [Let the] The magnitude of [a] the vector obtained by projecting the projective component vector $H_m{}^P(r-r_c, \theta_c, t)$ in the direction of the vector $e_{p,1}$, including the direction of the vector, [be] is represented (S4) by a value of $H_{m,1}{}^P(r-r_c, \theta_c, t)$. That is,

$$H_{\mathrm{m},1}{}^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)=\mathbf{H}_{\mathrm{m}}{}^{\mathrm{P}}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\cdot\mathbf{e}_{\mathrm{p},1}. \qquad (4)$$

$$\mathbf{e}_{\mathrm{p},1}=\mathbf{e}_{\mathrm{m}}\times\mathbf{e}_{\mathrm{n}}(\mathbf{r}). \qquad (5)$$

The next step is to calculate a vector $e_{p,2}$ perpendicular to the [directions] direction of the vectors $e_{p,1}$ and $e_n(r)$. The direction of the vector $e_{p,2}$ is also

perpendicular to the direction of the vector $e_n(r)$ [,] and hence [it is] contained in the plane of projection and [is] perpendicular to the direction of the vector $e_{p,1}$ as well. [Letting] If the projection of the projective component vector $H_m^P(r-r_c, \theta_c, t)$ in this direction [be] is represented by $H_{m,2}^P(r-r_c, \theta_c, t)$, values $H_{m,1}^P(r-r_c, \theta_c, t)e_{p,1}$ and $H_{m,2}^P(r-r_c, \theta_c, t)e_{p,2}$ [are] represent two independent vectors into which the projective component vector $H_m^P(r-r_c, \theta_c, t)$ is separated. Here,

$$H_{m,2}^{P}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)=\mathbf{H}_m^{P}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot\mathbf{e}_{p,2}. \quad (6)$$

$$\mathbf{e}_{p,2}=\mathbf{e}_{p,1}\times\mathbf{e}_n(\mathbf{r}). \quad (7)$$

[Then, by] By setting the position vector r_c and the angle [-] of [-] orientation θ_c of the magnetic field source so that a theoretically calculated magnetic field, $H_e(r-r_c, \theta_c, t)$ generated by the magnetic field source of the position vector r substantially matches [with a] the projective component $H_e^P(r-r_c, \theta_c, t)$ on the same plane as that of the measured magnetic field, it [is] becomes possible to detect the position and orientation of the magnetic field source.

The above [description has been given of a case] analysis treats a situation where the number of noise magnetic fields is virtually one [, but when] . When the number of noise magnetic fields is two, [letting] the direction of two noise magnetic fields $H_{n,j}(r, t)$, where j = 1, 2, may be represented by vectors $e_{n1}(r)$ and $e_{n2}(r)$, [use is made of] and the projection of the measured magnetic field on a direction vector $e_N(r)=e_{n1}(r)\times e_{n2}(r)$ in the coordinate system of Fig. 3 is used as depicted in Fig. 5. That is,

$$\mathbf{H}_m^{P}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)=\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)-\left(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot\mathbf{e}_N(\mathbf{r})\right)\mathbf{e}_N(\mathbf{r}). \quad (8)$$

is calculated (S11, S12, S13). In the above statement,

$$\mathbf{e}_N(\mathbf{r})=\mathbf{e}_{n1}(\mathbf{r})\times\mathbf{e}_{n2}(\mathbf{r}). \quad (9)$$

where the symbol "×" indicates a vector product. In this instance, an independent component in the projective component is one, that is, only the magnitude of the vector.

[Now, let] If the coordinates of the magnetic field source [be] are represented by [a] vector $r_c(x, y, z)$ and its angle of orientation by [a] vector $\theta_c(\theta_x, \theta_y, \theta_z)$[.] where [In the following description,] θ_x, θ_y and θ_z [will be] are referred to as an angle of rotation, a tilt angle and an azimuth, respectively [.] [When] , when the signal magnetic field is axially symmetric, the axis of symmetry is regarded as the x-axis, and the angle of orientation is set to [a] vector $\theta_c(\theta_y, \theta_z)$.

Further, according to the present invention, it is possible to calculate the magnitude $H_m(r-r_c, \theta_c)$ of each component of the original signal magnetic field vector $H_m(r-r_c, \theta_c, t)$ by using the synchronous detection of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ through the use of a proper one component in Eq. (1) or (6) that is a projective component.

$$\mathbf{H}_s(\mathbf{r}-\mathbf{r}_c,\ \theta_c)=\left\langle \mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)H_m^{P}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t. \qquad (10)$$

In the above, $H_m^P(r-r_c, \theta_c, t)$ is a proper component of the projective component given in Eq. (1) or (6).

Fig. 4 [shows the] illustrates a case where the number of noise magnetic field sources is essentially one. The processing of Fig. 4 is repeated at each measuring point. In [the case of] a situation where there are essentially two noise magnetic fields, [too,] the processing shown in Fig. 5 is similarly repeated at each measuring point as is the case with Fig. 4.

The magnitude $H_m(r-r_c, \theta_c)$ of the original signal magnetic field $H_m(r-r_c, \theta_c, t)$ can be obtained by calculating Eq. (10) after calculating the projective component at each measuring point. Concretely, the [processing depicted] process shown in Fig. 6 or 7 is [carried out] performed [(S11, S12, S14, S15, S16)

or (S11, S12, S14a, S16)].

HOW TO CALCULATE THE POSITION AND ANGLE OF ORIENTATION:

(1) Definitions of the coordinate system and the angle of orientation:

[A definition will be given first of the coordinate system necessary for the description of the invention.]

A coordinate system is set [which] , one that is fixed to the earth with the z-axis in a vertical direction (upward) [,] . This [which] system will hereinafter be referred to as [a] the measuring coordinate system vector C_M. The x- and y-axes are properly set so that they form a right-hand system. For example, they are [set in] parallel to the direction of projection of [in which] the side of a measuring frame [is projected on] onto a horizontal plane.

[This has for its object] The goal here is to calculate the coordinate vector $r_e(x, y, z)$ and the angle-of orientation vector $\theta_c(\theta_x, \theta_y, \theta_z)$ of the magnetic field source in the coordinate system.

[On the other hand, as] Like the coordinate system vector C_c of the magnetic field source, a coordinate system with the axial direction of the magnetic field source as the x axis is [set] disposed so that the y- and z- axes are horizontal and vertical (upward), respectively, when the magnetic field source is placed horizontally.

The angle-of-orientation vector θ_c of the magnetic field source is defined as the angle of rotation between the measuring coordinate system vector C_M and the coordinate system vector C_c [,] as described below. First [In the first place], a coordinate system C_{c0} parallel to the measuring coordinate system vector C_M is turned by an azimuth angle θ_z about the z-axis (in either [one of the] coordinate system). This coordinate system will be referred to as a coordinate system vector C_{c1}. Next, the coordinate system vector C_{c1} is turned by a tilt angle θ_y about the y-axis of the coordinate system vector C_{c1} itself. This coordinate system will be referred to as [a] the coordinate system vector C_{c2}. [Further] Additionally, the coordinate system vector C_{c2} is turned by an angle of rotation θz about the x-axis

of the coordinate system vector C_{c2} itself. The angle-of-orientation vector θ_c is determined so that the resulting coordinate system becomes the coordinate system vector C_c.

(2) Explanation of independent measurands and unknowns:

When the number of noise magnetic fields is essentially one, the measurement of the magnetic field at one place will provide two independent measured parameters [measurands] ("measurands"). When the number of noise magnetic fields is essentially two, the measurement of the magnetic field at one place will provide one independent measurand. [Further, in case of obtaining] In situations where components of the original signal magnetic field are obtained by synchronous detection, the measurement of the magnetic field at one place will provide three independent measurands. [On the other hand,] In contrast, three coordinate components of the coordinate vector $r_c(x, y, z)$ of the magnetic field source are unknowns. The azimuth angle θ_z is not obtainable without a different criterion such as the direction of the earth magnetism, and [hence it] therefore the azimuth angle is also an unknown unless the digging head is provided with a direction sensor. When the digging head is made of a magnetic material, or when a buried steel pipe or similar magnetic body lies near the digging head, an accurate direction cannot be obtained even if the direction sensor is provided [;] , and so [hence,] the azimuth angle θ_z is an unknown in many cases. The tilt angle θ_y can easily be detected by a tilt angle sensor that detects the vertical direction, and hence it is known in many cases. The same is true of the angle of rotation θ_x. In particular, when the signal magnetic field is axially symmetric, if the axis of symmetry is regarded as the x-axis, the angle of rotation θ_x becomes meaningless and [hence] can be ignored.

At any rate, measured magnetic fields need only to be obtained at different positions so that independent measurands are larger in number than unknowns.

Arrangement of the measuring system:

[For example, as] As shown in Fig. 1, for example, magnetic fields are

measured using a required number of three-axis magnetic sensors disposed on the ground so that their relative positions are known. [Since] Because the direction of the noise magnetic field changes for each position of measurement, it is necessary to perform for each position the step (S21) for detecting the position of the noise magnetic field and the step (S22) for calculating the projective component of the measured magnetic field [,] as shown in Fig. 8 [, that is] a flowchart of the procedure for [position determination by] determining position according to the present invention. [In case of calculating] Where the component of the original signal magnetic field must be calculated by synchronous detection, the processing therefor (in a specified step) needs to be carried out for each position.

Flow of measurement processing:

[A detailed description will be given of the detection] Detecting (S21) [of] the direction of the noise magnetic field, [the calculation] calculating (S23) [of] the position of the signal magnetic field source [through the use of] using the projective component and [the calculation of] calculating the position f of the signal magnetic field [through the use of] using the signal magnetic field component will now be described.

[EMBODIMENTS]

SITUATION I: Virtually [Embodiment in the case of virtually] one noise magnetic field:

[In case of] When using the projective component [,] when the number of unknowns is $N_U (\geq 1)$ and the number of noise magnetic fields is virtually one, the projective component vector $H_m^P(r-r_c, \theta_c, t)$ expressed by Eq. (1) is calculated from magnetic vectors $H_m(r-r_c, \theta_c, t)$ measured at $N_U/2$ or more different positions, and the position vector r_c and the angle-of-orientation vector θ_c are determined (S31) as depicted in Fig. 9 . In this way [so that] a projective component vector at each magnetic field sensing point is essentially equal to the projective component vector $H_e^P(r-r_c, \theta_c, t)$ of a theoretically calculated magnetic field of the projective component at each position of measurement [, by which it is] Thus, it becomes

possible to detect (S32) the position and orientation of the magnetic field source.

In [case of using] a situation where the magnitude of the signal magnetic field synchronously detected by the projective component is used, the magnetic field is measured at $N_U/3$ or more different positions. When the number $N_U(\geq 1)$ of unknowns is even, the number of unknowns and the number of independent measurands can be made equal to each other [;] , and if setting magnetic field vector $H_m(r-r_c, \theta_c, t)$ is measured at positions $N_m=N_U/2$, a N_U number of such equations as given below need only to be solved.

$$\left\langle H_{m,q}{}^{P}(\mathrm{r}_k-\mathrm{r}_c,\ \theta_c,\ t)\right\rangle_t - H_{e,q}{}^{P}(\mathrm{r}_k-\mathrm{r}_c,\ \theta_c)=0,\ k=1,\ \ldots,N_m;\ q=1,\ 2. \quad (11)$$

where q = 1, 2 and represents two directions parallel to the plane of projection [but] and parallel to each other (S33). Accordingly, $H_{m,q}{}^{P}(r-r_c, \theta_c, t)$ and $H_{e,q}{}^{P}(r-r_c, \theta_c, t)$, where q = 1, 2, [are] represent the [magnitudes] magnitude of q-direction components of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ and the theoretical calculated magnetic field vector $H_e(r-r_c, \theta_c, t)$, respectively. [Let it be] It is assumed that the vector θ_c represents any one of θ_x, θ_y, θ_z, (θ_y, θ_z), (θ_z, θ_x), (θ_x, θ_y), $(\theta_x, \theta_y, \theta_z)$ and ϕ , and that the vector r_c represents any one of x, y, z, (y, z), (z, x), (x, y), (x, y, z) and ϕ, where ϕ represents an empty set.

For example, when [unknowns are] the position vector $r_c(x, y, z)$ and azimuth angle θ_z of the magnetic field source are unknown, the magnetic field is to be measured at two different positions and four equations such as given below are solved, by which it is possible to obtain (S34) the position vector $r_c(x, y, z)$ and azimuth angle θ_z of the magnetic field source.

$$\left\langle H_{m,q}{}^{P}(\mathrm{r}_k-\mathrm{r}_c,\ \theta_z,\ t)\right\rangle_t - H_{e,q}{}^{P}(\mathrm{r}_k-\mathrm{r}_c,\ \theta_z)=0,\ k=1,\ 2;\ q=1,\ 2. \quad (12)$$

In the above, $<.>_t$ represents a time average.

[As depicted in] In Fig. 10 [, when] the magnetic field is measured at N_m

(>$N_U/2$) different places more than $N_U/2$ in excess of the number N_U of unknowns, since a larger number of independent measurands than the number of unknowns can be obtained (S41, S42, S43) [,] . Here, the position $r_c(e, y, z)$ and the angle of orientation θ_z are calculated [which provide] and yield:

$$\min_{\mathbf{r}_c,\, \theta_c}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\left\langle H_{m,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_{e,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \tag{13}$$

where $<.>_t$ represents the time average and $\min_{r_c,\theta_z}\{.\}$ means that vectors r_c and θ_c are changed to obtain vectors r_c and θ_c , which [that] minimize the contents in { . }. Further, a symbol $w_{k,q}$ indicates weighting. The Eq. (13) can be replaced with the following equations (S44).

$$\min_{\mathbf{r}_c,\, \theta_c}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\sqrt{\left\langle\left|H_{m,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right|^2\right\rangle_t} - H_{e,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \tag{14}$$

$$\min_{\mathbf{r}_c,\, \theta_z}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\left\langle H_{m,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right\rangle_t - H_{e,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_z)\right|^2\right\}. \tag{15}$$

$$\min_{\mathbf{r}_c,\, \theta_z}\left\{\sum_{k=1}^{N_m}\sum_{q=1}^{2} w_{k,q}\left|\sqrt{\left\langle\left|H_{m,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t)\right|^2\right\rangle_t} - H_{e,q}^{\mathrm{P}}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_z)\right|^2\right\}. \tag{16}$$

It is assumed [Assume] that vectors r_c and θ_c in Eqs. (13), (14), (15) and (16) have the same meaning as in the case of Eq. (11).

In [the above description] this analysis it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal [having] that has passed through a band pass filter that permits the passage [therethrough] of only those components close to the frequency of the signal magnetic field , or a wide-band signal that [is inhibited from the passage] cannot pass through the band pass filter [,] . However, using a signal that has passed [but the use of the signal having passed] through the band pass filter increases the [possibility] likelihood that [of

determining] the position of the magnetic field will be determined with a high degree of [with high] reliability.

SITUATION II: Essentially two noise magnetic fields:

[(Embodiment in the case of essentially two noise magnetic fields)]

When the number of unknowns is N_U (≥1) and the number of noise magnetic fields is virtually two, the projective component vector $H_m^P(r-r_c, \theta_c, t)$ expressed by Eq. (4) is calculated from magnetic vectors $H_m(r-r_c, \theta_c, t)$ measured at $N_U/2$ or more different positions, and the position vector r_c and the angle-of-orientation vector θ_c are determined (S51, S52) as depicted in Fig. 11 . Thus, [so that] the above-mentioned projective component vector obtained at each position of measurement essentially matches [with] the projective component vector $H_e^P(r-r_c, \theta_c, t)$ of a theoretically calculated magnetic field at each position of measurement [,] . By this means [by which] it is possible to detect (S53) the position and orientation of the magnetic field source.

In this [case] situation, the number N_U (≥1) of unknowns and the number of independent measurands can always be made to be equal to each other [without fail]; the magnetic field vector $H_m(r-r_c, \theta_c, t)$ is measured at different positions of the same number as that N_U number of unknowns, and N_U number of such equations given below need only to be solved.

$$\left\langle H_m{}^P(\mathrm{r}_k - \mathrm{r}_c,\ \theta_c,\ t)\right\rangle_t - H_e{}^P(\mathrm{r}_k - \mathrm{r}_c,\ \theta_c) = 0,\ k = 1,\ \ldots,N_U. \qquad (17)$$

[In this case,] Here, the symbols $H_m^P(r-r_c, \theta_c, t)$ and $H_e^P(r-r_c, \theta_c, t)$ are the respective magnitudes of the projective component vector $H_m^P(r-r_c, \theta_c, t)$ and the vector $H_e^P(r-r_c, \theta_c, t)$ of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ and the theoretical calculated magnetic field vector $H_e(r-r_c, \theta_c, t)$. [Let it be] It is assumed that the vector θ_c represents any one of θ_x, θ_y, θ_z, (θ_y, θ_z), (θ_z, θ_x), (θ_x, θ_y), (θ_x, θ_y, θ_z) and ϕ and that the vector r_c represents any one of x, y, z, (y, z), (z, x), (x, y), (x, y, z) and ϕ, where ϕ represents an empty set.

For example, when [unknowns are] the position vector $r_c(x, y, z)$, azimuth angle θ_z and tilt angle θ_y of the magnetic field source are unknowns, the magnetic field is to be measured at five different positions and four such equations given below are to be solved, by which it is possible to obtain the position vector $r_c(x, y, z)$, the azimuth angle θ_z and the tilt angle θ_y of the magnetic field source.

$$\left\langle H_{\mathrm{m}}^{\mathrm{P}}(\mathbf{r}_{\mathrm{k}} - \mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right\rangle_t - H_{\mathrm{e}}^{\mathrm{P}}(\mathbf{r}_{\mathrm{k}} - \mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}}) = 0,\ k = 1,\ \ldots,5. \tag{18}$$

In the above, $<.>_t$ represents a time average[. And] , and the vector $\theta_c = \theta_c(\theta_y, \theta_z)$.

Because a greater number of independent measurands than the number of unknowns can be obtained (S61, S62), as [As depicted] seen in Fig. 12, when the magnetic field is measured at N_m ($>N_U$) different places more than N_U in excess of the number N_U of unknowns, [since a larger number of independent measurands than the number of unknowns can be obtained (S61, S62),] the position $r_c(e, y, z)$ and the angle of orientation θ_z are calculated [which provide] , yielding

$$\min_{\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}}}\left\{\sum_{k=1}^{N_{\mathrm{m}}} w_k \left|\left\langle H_{\mathrm{m}}^{\mathrm{P}}(\mathbf{r}_{\mathrm{k}} - \mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right\rangle_t - H_{\mathrm{e}}^{\mathrm{P}}(\mathbf{r}_{\mathrm{k}} - \mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}})\right|\right\}. \tag{19}$$

where $<.>_t$ represents the time average and $\min\limits_{r_c,\theta_z}\{.\}$ means that vectors r_c and θ_c are changed to obtain an r_c and a θ_c that minimize the contents in { . }. [Further, a] The symbol $w_{k,q}$ indicates weighting. [The] Eq. (19) can be replaced with the following equations (S63).

$$\min_{\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}}}\left\{\sum_{k=1}^{N_{\mathrm{m}}} w_k \left|\sqrt{\left\langle \left|H_{\mathrm{m}}^{\mathrm{P}}(\mathbf{r}_{\mathrm{k}} - \mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right|^2\right\rangle_t} - H_{\mathrm{e}}^{\mathrm{P}}(\mathbf{r}_{\mathrm{k}} - \mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}})\right|\right\}. \tag{20}$$

$$\min_{\mathbf{r}_c,\,\theta_z}\left\{\sum_{k=1}^{N_m} w_k \left| \left\langle H_m^{\,P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t) \right\rangle_t - H_e^{\,P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c) \right|^2 \right\}. \qquad (21)$$

$$\min_{\mathbf{r}_c,\,\theta_z}\left\{\sum_{k=1}^{N_m} w_k \left| \sqrt{\left\langle \left| H_m^{\,P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c,\ t) \right|^2 \right\rangle_t} - H_e^{\,P}(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c) \right|^2 \right\}. \qquad (22)$$

[Assume] Here it is assumed that r_c and θ_c in Eqs. (19), (20), (21) and (22) have the same meaning as in [the case of] Eq. (16).

In the above analysis [description], it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal [having] that has passed through a band pass filter that permits the passage [therethrough] of only those components close to the frequency of the signal magnetic field, or a wide-band signal that [is inhibited from the passage] cannot pass through the band pass filter [,] However, [but] the use of the signal [having] that has passed through the band pass filter increases the [possibility] likelihood of determining the position of the magnetic field with [high] great deal of reliability.

Further, in [case of using] a situation where the signal magnetic field component is obtained by synchronous detection, the direction of the noise magnetic field is determined and is used to obtain the projective magnetic field [; and the] ___. The subsequent processing is [common to the cases] characteristic of the situations of both one and two noise magnetic fields. The projective component vectors $H_m^P(r-r_c, \theta_c, t)$ at their respective places are calculated from the magnetic field vectors $H_m(r-r_c, \theta_c, t)$ measured at $N_U/3$ or more different places, and a proper one of the calculated vectors is used as a reference signal to perform the synchronous detection of the measured magnetic field vectors $H_m(r-r_c, \theta_c, t)$ [, thereby] ___. Thus, [obtaining] the magnitude $H_s(r-r_c, \theta_c)$ of the original signal magnetic field component is obtained. By determining the position vector r_c and the angle-of-orientation vector θ_c of the magnetic field source so that the magnitude of the original signal magnetic field component and the magnitude $H_c(r-r_c, \theta_c)$ of the theoretical signal component are equal to each other, it is

possible to detect the position and orientation of the magnetic field source.

When the number N_U (≥ 1) of unknowns is a multiple of 3, the number of unknowns and the number of independent measurands can be made to be equal to each other; if the magnetic field vector $H_m(r-r_c, \theta_c, t)$ is measured at positions $N_m = N_m/N_U/3$, N_U number of such equations, as given below, [need] needs only [to] be solved.

$$\mathbf{H}_s(\mathbf{r}_k - \mathbf{r}_c, \theta_c) - \mathbf{H}_c(\mathbf{r}_k - \mathbf{r}_c, \theta_c) = 0, \; k = 1, \ldots, N_m. \tag{23}$$

Fig. 13 shows the flow of this process [processing] (S61, S62, S65). Here, $H_s(r-r_c, \theta_c)$ and $H_c(r-r_c, \theta_c, t)$ are the signal magnetic field calculated from the measured magnetic field vectors $H_m(r-r_c, \theta_c, t)$ and the magnitude of the theoretical calculated magnetic field vector, respectively. The magnitude $H_s(r-r_c, \theta_c)$ of the signal magnetic field vector is an averaged quantity , as already explained. [Let it be] It is assumed that the vector θ_c represents any one of θ_x, θ_y, θ_z, (θ_y, θ_z), (θ_z, θ_x), (θ_x, θ_y), (θ_x, θ_y, θ_z) and ϕ , and that the vector r_c represents any one of x, y, z, (y, z), (z, x), (x, y), (x, y, z) and ϕ, where ϕ represents an empty set.

For example, when [an unknown is] the position vector $r_c(x, y, z)$ of the magnetic field source is an unknown, the magnetic field is to be measured at one place and three such equations (as given below) are solved, by which it is possible to obtain the position vector $r_c(x, y, z)$ and the azimuth angle θ_z of the magnetic field source.

$$\mathbf{H}_s(\mathbf{r} - \mathbf{r}_c) - \mathbf{H}_c(\mathbf{r} - \mathbf{r}_c) = 0. \tag{24}$$

The vector r is the vector of the position of measurement.

Because a larger number of independent measurands than the number of unknowns can be obtained when [When] the magnetic field is measured at N_m (>$N_U/2$) different places more than N_U in excess of the number N_U of unknowns,

[since a larger number of independent measurands than the number of unknowns can be obtained,] the position $r_c(e, y, z)$ and the angle of orientation θ_z are calculated [which provide] , yielding

$$\min_{r_c,\ \theta_c}\left\{\sum_{k=1}^{N_m} w_k \left|\mathbf{H}_s(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)-\mathbf{H}_c(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|\right\}. \qquad (25)$$

where $\min_{r_c,\theta_z}\{\ .\}$ means that vectors r_c and θ_c are changed to obtain the vectors r_c and θ_c that minimize the contents in { . }. Further, [a] the symbol $w_{k,q}$ indicates weighting. [The] Eq. (25) can be replaced with the following equations.

$$\min_{r_c,\ \theta_c}\left\{\sum_{k=1}^{N_m} w_{k,}\left(\left\|\mathbf{H}_s(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right\|-\left\|\mathbf{H}_c(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right\|\right)^2\right\}. \qquad (26)$$

$$\min_{r_c,\ \theta_z}\left\{\sum_{k=1}^{N_m} w_k \left|\mathbf{H}_s(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)-\mathbf{H}_c(\mathbf{r}_k-\mathbf{r}_c,\ \theta_c)\right|^2\right\}. \qquad (27)$$

Fig. 14 shows the flow of this process [processing] (S61, S64, S66).

[A description will be given below of how to determine the direction of the noise magnetic field in the two embodiments described above.]

DETERMINING THE DIRECTION OF THE NOISE MAGNETIC FIELD.

With virtually one noise magnetic field.

[(How to determine the direction of the noise magnetic field in the case of virtually one noise magnetic field)]

[(First method)]

Method (1). The first method for determining the direction of the noise magnetic field is [a method] used where, in [case of] a situation with no signal magnetic field, a noise magnetic field is measured [through the use of] using the same measuring system as [that] for measuring the signal magnetic field. This

type of situation is [such as] shown in Fig. 15 , where [in which] the detection of the digging position is disturbed by a noise magnetic field source lying in the vicinity of the digging route. Another [case] situation is [that] where the signal magnetic field source is [equipped with a function of receiving] is able to receive a command sent, for example, from the ground by some means and is responsive to the command to stop [the generation of] generating the signal magnetic field.

In this instance, as depicted in Fig. 16, [letting] if the measured magnetic field [be] is represented by a vector $H_m(r{-}r_c,\ \theta_c,\ t)$, [since] because this is essentially a noise magnetic field vector $H_n(r,\ t)$ as shown at a step (S71), an average value of its absolute values can be used (S72) to calculate [a] the direction vector, $e_n(r)$=$e_{n,x}(r)$, $e_{n,y}(r)$, $e_{n,z}(r)$), of the noise magnetic field as follows:

$$e_{\mathrm{n},\,\alpha}(\mathbf{r})=\frac{\left\langle\left|H_{\mathrm{m},\,\alpha}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right|\right\rangle_{t}}{\sqrt{\sum_{\alpha=x,\,y,\,z}\left\langle\left|H_{\mathrm{m},\,\alpha}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right|\right\rangle^{2}}},\qquad \alpha=x,\ y,\ z. \tag{28}$$

Alternatively, a root-mean-square value of the above absolute values can be used to determine the direction of the noise magnetic field by use of the equation

$$e_{\mathrm{n},\,\alpha}(\mathbf{r})=\frac{\sqrt{\left\langle\left(H_{\mathrm{m},\,\alpha}(\mathbf{r}_{\mathrm{k}}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right)^{2}\right\rangle_{t}}}{\sqrt{\sum_{\alpha=x,\,y,\,z}\left\langle\left(H_{\mathrm{m},\,\alpha}(\mathbf{r}_{\mathrm{k}}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ t)\right)^{2}\right\rangle_{t}}},\qquad \alpha=x,\ y,\ z. \tag{29}$$

In this case, [a] the symbol $H_{m,\alpha}(r{-}r_c,\ \theta_c,\ t)$ is an α component of the measured magnetic field (the noise magnetic field), and α is any one of x, y and z.

In the analysis above , [description] it does not matter whether the measured magnetic field vector $H_m(r{-}r_c,\ \theta_c,\ t)$ is a signal [having] that has passed through a band pass filter that permits the passage [therethrough] of only those components close to the frequency of the signal magnetic field , or a wide-band

signal that [is inhibited from the passage] cannot pass through the band pass filter [,] . [but] However, the use of the signal [having] that has passed through the band pass filter increases the [possibility] likelihood of determining the position of the magnetic field with [high] a great deal of reliability.

[(Second method)]

Method (2).

Step 1

[As shown in] Turning now to Fig. 17, [at] first [,] the frequency spectrum $H_m(\omega)$ of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is calculated (S81, S82, S83) by means of the following equation.

$$\mathbf{H}_m(\omega) = \mathrm{F}\left(\mathbf{H}_m(\mathbf{r}_k - \mathbf{r}_c,\ \theta_c,\ t)\right) \qquad (30)$$

In this case, [a] the symbol F(.) represents a Fourier transform; the three components x, y and z of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ are each Fourier transformed. In practice, the above-mentioned frequency spectrum can be calculated by FFT (fast Fourier transform) or the like of sampled values of the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$.

Step 2

Next, an angular frequency ω_i, where $i = 1, 2, \ldots, N_s$, of a large-amplitude component, such as a line spectrum, is selected (S84) from the absolute value $|H_m(\omega)|$ of the frequency spectrum. For the component of each angular frequency ω_i, where $i = 1, 2, \ldots, N_{ns}$, a candidate unit vector $e_n(r, \omega_i)$, where $i = 1, 2, \ldots, N_{ns}$, of the direction of the noise magnetic field, is calculated (S85) by [the] either method (1) or (2) [described] below.

(1) The absolute values of the Fourier-transformed x, y, and z components of the angular frequency concerned are used to calculate the candidate unit vector $e_n(r, \omega_i)$, where $i = 1, 2, \ldots, N_{ns}$, of the direction of the noise magnetic field, by the following procedures:

(2)

$$\mathbf{e}_{\mathrm{n}}(\mathbf{r},\omega_{\mathrm{i}})=\frac{\left(\left|\mathrm{H}_{\mathrm{m},x}(\omega_{\mathrm{i}})\right|\ \left|\mathrm{H}_{\mathrm{m},x}(\omega_{\mathrm{i}})\right|\ \left|\mathrm{H}_{\mathrm{m},x}(\omega_{\mathrm{i}})\right|\right)}{\sqrt{\sum_{\alpha=x,y,z}\left|\mathrm{H}_{\mathrm{m},\alpha}(\omega_{\mathrm{i}})\right|^{2}}},\quad i=1,\ \dots,\ N_{\mathrm{ns}}. \tag{31}$$

where $H_{m,\alpha}(\omega_i)$, [where] α = x, y, z and i = 1, 2, …, N_{ns}, is a ω_i component by the Fourier transform of the α component of the measured magnetic field.

(3) A narrow-band filter is formed <u>the</u> [whose] pass band <u>of which</u> uses, as the center frequency, the angular frequency ω_i, where i = 1, 2, …, N_{ns}, and the [same method as by] <u>of</u> Eq. (21) or (22) is used to calculate the candidate unit vector $e_n(r, \omega_i)$, where i = 1, 2, …, N_{ns}. That is, the candidate unit vector $e_n(r, \omega_i)= (e_{n,x}(r), e_{n,y}(r), e_{n,z}(r))$, where i = 1, 2, …, N_{ns} ,is calculated by

$$e_{\mathrm{n},\alpha}(\mathbf{r},\ \omega_{\mathrm{i}})=\frac{\left\langle\left|H_{\mathrm{m},\alpha}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ \omega_{\mathrm{i}},\ t)\right|\right\rangle_{\mathrm{t}}}{\sqrt{\sum_{\alpha=x,y,z}\left\langle\left|H_{\mathrm{m},\alpha}(\mathbf{r}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ \omega_{\mathrm{i}},\ t)\right|\right\rangle^{2}}},\quad \alpha=x,\ y,\ z;\ i=1,\ \dots,\ N_{\mathrm{ns}}. \tag{32}$$

or by

$$e_{\mathrm{n},\alpha}(\mathbf{r},\ \omega_{\mathrm{i}})=\frac{\sqrt{\left\langle\left(H_{\mathrm{m},x}(\mathbf{r}_{\mathrm{k}}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ \omega_{\mathrm{i}},\ t)\right)^{2}\right\rangle_{\mathrm{t}}}}{\sqrt{\sum_{\alpha=x,y,z}\left\langle\left(H_{\mathrm{m},\alpha}(\mathbf{r}_{\mathrm{k}}-\mathbf{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ \omega_{\mathrm{i}},\ t)\right)^{2}\right\rangle_{\mathrm{t}}}},\quad \alpha=x,\ y,\ z;\ i=1,\ \dots,\ N_{\mathrm{ns}}. \tag{33}$$

<u>Step 3</u>

The candidate unit vector $e_n(r, \omega_i)= (e_{n,x}(r), e_{n,y}(r), e_{n,z}(r))$, where i = 1, 2, …, N_{ns} , is considered as the direction vector $e_n(r)$ of the noise magnetic field, and for each angular frequency ω_i, where i = 1, 2, …, N_{ns} , the [same] method [as by] <u>of</u> Eq. (1) is used to calculate a projective component vector $H_m^P(r-r_c, \theta_c, \omega_i, t)$.

$$\mathbf{H}_m{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ \omega_i,\ t)=\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)$$
$$-\left(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\cdot\mathbf{e}_n(\mathbf{r},\ \omega_i)\right)\mathbf{e}_n(\mathbf{r},\ \omega_i),\ i=1,\ \ldots,\ N_{ns}. \qquad (34)$$

[The reason for which the] The angular frequency ω_i is contained as a variable of the projective component [is] so as to explicitly point out that the projective component is dependent on the angular frequency ω_i, where $i = 1, 2, \ldots, N_{ns}$. A roper time interval T_{test}, which consists of N_{test} durations $T_{t,k}$, where $k = 1, 2, \ldots, N_{test}$, each having a short time length Δt, is chosen, and the variation of the projective component vector $H_m{}^P(r-r_c, \theta_c, \omega_i, t)$ for each duration $T_{t,k}$, where $k = 1, 2, \ldots, N_{test}$, is evaluated (S86). [Assume] It is assumed, here, that each duration $T_{t,k}$, where $k = 1, 2, \ldots, N_{test}$ does not overlap other durations. [Concretely] More concretely, a [variance] variation of N_{test} statistics $v_{eval,k}(\omega_i)$ of the N_{test}, where $k = 1, \ldots, N_{test}$, which are [calculated] determined by any one of the methods described below, is calculated.

(1) One or both of the means of absolute values of two orthogonal components by

$$v_{eval,\ k}(\omega_i)=\left\langle\left|H_{m,\ q}{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ \omega_i,\ t)\right|\right\rangle_{T_{t,k}},\ q=1,\ 2;\ k=1,\ \ldots,\ N_{test};\ i=1,\ \ldots,\ N_{ns}. \qquad (35)$$

where $\langle\cdot\rangle_{Tt,k}$ represents the mean value in the duration $T_{t,k}$ and $v_{eval,k}$ is a statistic calculated for the duration $T_{t,k}$.

(2) Mean of absolute values

$$v_{eval,\ k}(\omega_i)=\left\langle\left|\mathbf{H}_m{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ \omega_i,\ t)\right|\right\rangle_{T_{t,k}},\ k=1,\ \ldots,\ N_{test};\ i=1,\ \ldots,\ N_{ns}. \qquad (36)$$

(3) One or both of the means of squares of two orthogonal components by

$$v_{eval,\ k}(\omega_i)=\left\langle\left(H_{m,\ q}{}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ \omega_i,\ t)\right)^2\right\rangle_{T_{t,k}},\ q=1,\ 2;\ k=1,\ \ldots,\ N_{test};\ i=1,\ \ldots,\ N_{ns}.$$

(37)

(4) One or both of square roots of the means of squares of two orthogonal components by

$$v_{\mathrm{eval,\,k}}(\omega_{\mathrm{i}}) = \sqrt{\left\langle \left(H_{\mathrm{m,\,q}}{}^{\mathrm{P}}(\mathrm{r}-\mathrm{r}_{\mathrm{c}},\ \theta_{\mathrm{c}},\ \omega_{\mathrm{i}},\ t) \right)^2 \right\rangle_{\mathrm{T_{t,k}}}},\ q=1,\ 2;\ k=1,\ \ldots,\ N_{\mathrm{test}};\ i=1,\ \ldots,\ N_{\mathrm{ns}}.$$

(38)

For the statistics $v_{eval,k}$, where $k = 1, \ldots, N_{test}$, calculated by these equations, the following equation is [calculated] applied to obtain (S86) a value of $\omega_{i,min}$ that is the angular frequency ω_i [which] that minimizes var(ω_i) [.] :

$$\mathrm{var}(\omega_{\mathrm{i}}) = \frac{\sqrt{\mathrm{mean}_{\mathrm{k}}\left(\left(v_{\mathrm{eval,\,k}}(\omega_{\mathrm{i}}) - \mathrm{mean}_{\mathrm{k}}\left(v_{\mathrm{eval,\,k}}(\omega_{\mathrm{i}}) \right) \right)^2 \right)}}{\mathrm{mean}_{\mathrm{k}}\left(v_{\mathrm{eval,\,k}}(\omega_{\mathrm{i}}) \right)},\ i=1,\ \ldots,\ N_{\mathrm{ns}}. \qquad (39)$$

In the above, $\mathrm{mean}_k(.)$ indicates averaging for the suffix k, that is,

$$\mathrm{mean}_{\mathrm{k}}(\,.\,) = \frac{\sum_{k=1}^{N_{\mathrm{test}}}(\cdot)}{N_{\mathrm{test}}}. \qquad (40)$$

The magnetic field of the angular frequency $\omega_{i,min}$ derives from the noise magnetic field, and the direction of the noise magnetic field becomes a vector $e_n(r, \omega_{i,min})$.

[Incidentally,] It should be noted that the angular frequency $\omega_{i,min}$, which minimizes var(ω_i), needs only to be measured at one place and need not be obtained at every place where to measure the magnetic field.

With this method, it is also possible to calculate a fluctuation in the direction of a vector $H_m^P(r-r_c, \theta_c, \omega_i, t)$, as well as an amplitude fluctuation

given by Eq. (39) , and to select the angular frequency $\omega_{i,min}$ at which the direction fluctuation becomes [minimum] minimal, or smaller than a predetermined value. [Incidentally, in] In the above description, the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ in Step 1 is a wide-band signal, and in Step 3 it does not matter whether the measured magnetic field vector $H_m(r-r_c, \theta_c, t)$ is a signal [having] that has passed through a band pass filter that permits the passage [therethrough] of only those components close to the frequency of the signal magnetic field or a wide-band signal that [is inhibited from the passage] cannot pass through the band pass filter [,] . However, [but] the use of the signal [having] that has passed through the band pass filter increases the [possibility] likelihood of determining the position of the magnetic field with high degree of reliability.

Fig. 18 shows how to select the frequencies $f_1(=\omega_1/2\pi)$, $f_2(=\omega_2/2\pi)$, ..., $f_n(=(\omega_n/2\pi$, where $n=N_{ns}$), at which the frequency spectrum becomes maximum; Fig. 19 shows the flow of [processing] the process, including step S91 , for obtaining the candidate vector; and Figs. 20 and 21 show the flow of [processing] the process, including steps S101 and S102 or steps S111 and S112 , for evaluating the candidate vector and for detecting the direction of the noise magnetic field.

The frequency spectrum $H_m(\omega)$ need not always be used. That is, the signal magnetic field is periodically turned OFF/ON [following] after a predetermined procedure; the period T_{period} is divided into equally [-] spaced durations; the candidate unit vector $e_n(r, t_i)$, where $i = 1, \ldots, N_{ns}$, is used in place of the candidate unit vector $e_n(r, \omega_i)$, where $i = 1, \ldots, N_{ns}$, which is calculated by Eqs. (25), (26) and (27); and , thereafter, the duration that minimized the [variance] variation by Eq. (33) is calculated by the [processing] process described above. [By] In this way, the vector $e_n(r, t_i)$ in that duration can be adopted as the direction of [he] the noise magnetic field.

[(Third method)]

Method (3). In the second method, the large-amplitude angular frequency ω_i, where i = 1, 2, ..., N_s, is selected from the absolute value $|H_m(\omega)|$ of the frequency spectrum $H_m(\omega)$ [, but] . However, the vector $e_n(r, \omega_{i,min})$ can be obtained as the direction of the noise magnetic field in exactly the same manner as in the case of the second method, by selecting a proper frequency band [neighboring] near the frequency of the signal magnetic field, setting properly [-] spaced test frequencies free from the frequency of the signal magnetic field in the frequency band and regarding the test frequencies as the angular frequency ω_i , as in the second method.

As is the case with the second method, the angular frequency $\omega_{i,min}$ at which var(ω_i) becomes minimum needs only to be obtained.

Fig. 22 shows how to select the frequencies $f_1(=\omega_1/2\pi)$, $f_2(=\omega_2/2\pi)$, ..., $f_n(=(\omega_n/2\pi$, where $n=N_{ns})$ at which the frequency spectrum [becomes maximum] is maximized. The flow of the subsequent [processing] process is the same as depicted in Figs. 17, 19 and 20.

[(Fourth method)]

Method (4). The signal magnetic field is periodically stopped under the control of a predetermined procedure. For example, the signal magnetic field is periodically stopped [by] at a predetermined time interval. [Since] Because the intensity of the magnetic field being measured decreases while the signal magnetic field is stopped, the OFF period of the signal magnetic field is identified by [regarding] interpreting the intensity-decreasing period essentially as [the] a predetermined OFF period [, and the] . The direction of the magnetic field measured during the OFF period is used as the direction of the noise magnetic field. The direction of the noise magnetic field can be obtained using the same method as the first one. Fig. 23 shows how the amplitude of the measured magnetic field in this method varies [with] over time.

[(Fifth method)]

[The] Method (5). Here, the signal magnetic field is periodically

stopped [following] after a predetermined procedure. This is carried out as described below [under] as options (1) and (2).

(1) To stop the signal magnetic field on a rectangular-wave-wise:

The signal magnetic field is repeatedly turned ON and OFF with the period T_{period}, for instance.

$$\begin{aligned} s(t) &= 1, \quad t_k \le t < t_k + t_{stop}. \\ &= -1, \quad t_k + t_{stop} \le t \le t_{k+1}. \end{aligned} \tag{41}$$

[and when] When a sequence s(t) is 1, the signal magnetic field is turned OFF, but when the sequence is −1, the signal magnetic field is turned ON. In the above,

$$t_{k+1} - t_k = T_{period}, \ k = 1,\ 2,\ 3,\ \ldots \tag{42}$$

(2) To stop the signal magnetic field on a pseudo-random-signal-wise basis[: For] , for example, when the value is "−1" in a random sequence like an M-sequence consisting of unit periods T_{unit} of the same length N_M, the signal magnetic field is turned ON, but when the value is "1," the signal magnetic field is turned OFF; and this sequence is repeated. In this case, the time average of the sequence is set to 0.

Fig. 24 shows temporal variations in the amplitude of the measured magnetic field [in the case of] when the signal magnetic field [being] is stopped by [the] method (1). Fig. 25 shows temporal variations in the amplitude of the measured magnetic field [in the case of] when the signal magnetic field [being] is stopped by [the] method (2).

Next, as depicted in Fig. 26, the correlation function between the sequence s(t) and the norm of the measured magnetic field or the absolute value of its particular component is calculated (S121, S122, S123). As the correlation

function, it is possible to use any one of [those calculated by] the equations given below:

$$R(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \left|\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right| s(t-\tau)dt. \tag{43}$$

$$R(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \sqrt{\left(\mathbf{H}_m(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-\tau)dt. \tag{44}$$

$$R_\alpha(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \left|H_{m,\,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right| s(t-\tau)dt,\ \alpha=x,y,z. \tag{45}$$

$$R_\alpha(\tau)=\int_{t_k}^{t_k+N_T T_{period}} \sqrt{\left(H_{m,\,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-\tau)dt,\ \alpha=x,y,z. \tag{46}$$

In this case, the period for [which to detect] detecting the correlation is set to an integral multiple $N_T T_{period}$ of the period T_{period}.

The OFF state of the signal magnetic field can be detected (S125) from the time $\tau=t_{sync}$ at which time any one of the above correlation functions [become maximum] is maximized (S124). That is, a sequence $s(t-t_{sync})$, which starts at the time $\tau=t_{sync}$, is used, and when the sequence s(t) is "1," the signal magnetic field is regarded as being OFF; in this way, the ON/OFF operation of the signal magnetic field is determined.

In [the thus determined] a signal magnetic field OFF period determined in this way, the direction of the measured magnetic field is detected, and [the] that direction is regarded as the direction of the noise magnetic field (S126). When the sequence s(t) is "–1" (a second numerical value), the signal magnetic field is turned ON, and when the sequence is "1" (a first numerical value), the signal magnetic field is turned OFF; this sequence is repeated in this way.

[(Sixth method)]

Method (6). As [is the case] with the fifth method, the signal magnetic field is periodically stopped under the control of [such] a predetermined procedure

as described below.

(1) To stop the signal magnetic field on a rectangular-wave-wise:

The signal magnetic field is repeatedly turned ON and OFF with the period T_{period}, for [instance] example.

$$
\begin{aligned}
s(t) &= 1, \quad t_k \le t < t_k + t_{stop}. \\
&= -1, \quad t_k + t_{stop} \le t \le t_{k+1}.
\end{aligned}
\tag{41}
$$

[and when a] When the sequence s(t) is 1, the signal magnetic field is turned OFF [, but when] . When the sequence is −1, the signal magnetic field is turned ON. In the above,

$$
t_{k+1} - t_k = T_{period}, \; k = 1,\ 2,\ 3,\ \ldots \tag{42}
$$

(2) To stop the signal magnetic field on a pseudo-random-signal-wise basis:

For example, when the value is "−1" in a random sequence like an M-sequence consisting of unit periods T_{unit} of the same length N_M, the signal magnetic field is turned ON, but when the value is "1," the signal magnetic field is turned OFF; and this sequence is repeated.

In this case, the sequence s(t) is chosen so that it changes for each predetermined time unit Δt_{unit}. [And, the] The [time] average of the sequence is "0."

Next, as depicted in Fig. 27, the correlation function between the sequence s(t) and the norm of the measured magnetic field or the absolute value of its particular component is calculated (S131, S132, S133) as in [case of] the fifth method. [As the correlation function, it] It is possible to use any one of [those calculated by] the following correlation functions:

$$R(\tau) = \int_{k}^{t_k + N_T T_{period}} \left| \mathbf{H}_m(\mathbf{r} - \mathbf{r}_c,\ \theta_c,\ t) \right| s(t-\tau)dt. \tag{43}$$

$$R(\tau) = \int_{k}^{t_k + N_T T_{period}} \sqrt{\left(\mathbf{H}_m(\mathbf{r} - \mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-\tau)dt. \tag{44}$$

$$R_\alpha(\tau) = \int_{t_k}^{t_k + N_T T_{period}} \left| H_{m,\alpha}(\mathbf{r} - \mathbf{r}_c,\ \theta_c,\ t) \right| s(t-\tau)dt,\ \alpha = x, y, z. \tag{45}$$

$$R_\alpha(\tau) = \int_{t_k}^{t_k + N_T T_{period}} \sqrt{\left(H_{m,\alpha}(\mathbf{r} - \mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-\tau)dt,\ \alpha = x, y, z. \tag{46}$$

[In this case, the] Here, the period for [which to detect] detecting the correlation is set to an integral multiple $N_T T_{period}$ of the period T_{period}.

In this instance, there are present, in general, plural times $\tau = t_{sync,k}$ ($k = 1, 2, \ldots, N_{sync}$) [in] at which the correlation function [becomes maximum] is maximized and the maximum value exceeds a predetermined value (S134). [Assume, for example,] It is assumed that $t_{sync,k}$, ($k = 1, 2, \ldots, N_{sync}$) is an arrangement of such times in temporal order [of time]. When the correlation value between the sequence s(t) and the signal magnetic field is appropriate,

$$\Delta t_{sync,\,k} = t_{sync,\,k} - t_{sync,\,1},\quad k = 2,\ \ldots,\ N_{sync}. \tag{47}$$

is virtually an integral multiple of the time unit Δt_{unit}. [Then, the] The average of the value resulting from the subtraction of an integral multiple $M_{sync,k}\Delta t_{unit}$ of the time unit Δt_{sync}, where $k = 2, \ldots, N_{sync,\,k}$, from $\Delta t_{sync,k}$, where $k = 2, \ldots, N_{sync}$, is then calculated [by] as

$$\delta t_{sync} = \frac{\sum_{k=2}^{N_{sync}} \left(\Delta t_{sync,\,k} - M_{sync,\,k}\Delta t_{unit}\right)}{N_{sync} - 1}. \tag{48}$$

In this case,

$$t_{sync} = t_{sync,1} + \delta t_{sync} \tag{49}$$

[provides] is the beginning of the sequence signal corresponding to the ON/OFF operation of the signal magnetic field.

[Accordingly,] Thus, the period during which the signal magnetic field is OFF can easily be set based on the sequence $s(t-t_{sync})$.

By applying the same method as [the first] method (1) to the magnetic field vector $H_m(r-r_c, \theta_c, t)$ measured in this period, the direction $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ can be calculated (S138).

[(Seventh method)]

[This method will be described below with] Method (7). With reference to Figs. 28, 29, 30 and 31 [.] , and as [As] is the case with the fifth method, the signal magnetic field is periodically stopped, for example, [by such] a procedure such as those described below.

(1) To stop the signal magnetic field on a rectangular-wave-wise:

The signal magnetic field is repeatedly turned ON and OFF with the period T_{period}, for instance.

$$\begin{aligned} s(t) &= 1, \quad t_k \le t < t_k + t_{stop}. \\ &= -1, \quad t_k + t_{stop} \le t \le t_{k+1}. \end{aligned} \tag{41}$$

and when a sequence s(t) is 1, the signal magnetic field is turned OFF, but when the sequence is −1, the signal magnetic field is turned ON. In the above,

$$t_{k+1} - t_k = T_{period}, \; k = 1, 2, 3, \ldots \tag{42}$$

(2) To stop the signal magnetic field on a pseudo-random-signal-wise basis:

For example, when the value is "−1" in a random sequence like an M-sequence consisting of unit periods T_{unit} of the same length N_M, the signal magnetic field is turned ON [, but when] . When the value is "1," however,

the signal magnetic field is turned OFF; and this sequence is repeated accordingly. In this case, the time average of the sequence is "0."

Next, the correlation function between the sequence s(t) and the measured magnetic field $H_m(r-r_c, \theta_c, t)$ is calculated (S141, S142, S143). The period T_{period} is divided into equally spaced N_{div} sections of a length T_{div}, and either [one of] the following calculations is [conducted] <u>performed</u>.

$$R_\alpha(t_k) = \int_{t_k}^{t_k+T_{period}} \left| H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t) \right| s(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \quad (50)$$

$$R_\alpha(t_k) = \int_{t_k}^{t_k+T_{period}} \sqrt{\left(H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, s(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \quad (51)$$

[In this case, a] <u>Here, the</u> symbol $R_\alpha(t_k)$, where α = x, y, z and k = 1, …, N_{div}, is the time correlation between an α component $H_{m,\alpha}(r-r_c, \theta_c, t)$ of the measured magnetic field $H_m(r-r_c, \theta_c, t)$ and the sequence s(t). And

$$t_k = t_0 + k \cdot T_{div},\quad k=1,\ \ldots,\ N_{div}. \quad (52)$$

The measured magnetic field may also be correlated with the time that is an m-multiple of the period T_{period}. That is,

$$R_\alpha(t_k) = \int_{t_k}^{t_k+mT_{period}} \left| H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t) \right| S_{mp}(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \quad (53)$$

$$R_\alpha(t_k) = \int_{t_k}^{t_k+mT_{period}} \sqrt{\left(H_{m,\alpha}(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t)\right)^2}\, S_{mp}(t-t_k)dt,\ k=1,\ \ldots,\ N_{div};\ \alpha = x,y,z. \quad (54)$$

In this instance, the sequence s(t) is replaced with $S_{mp}(t)$, where

$$\begin{aligned} S_{mp}(t) &= S(t+T_{period}) \\ S_{mp}(t) &= s(t),\ 0 \le t < T_{period}. \end{aligned} \quad (55)$$

[This is followed by calculating the] The component $H_m^P(r-r_c, \theta_c, t_k, t)$ is then calculated, where $k = 1, \ldots, N_{div}$, of the measured magnetic field $H_m(r-r_c, \theta_c, t)$ projected on the vector

$$\mathbf{e_n(t_k)=(R_x(t_k), R_y(t_k), R_z(t_k))}, \text{ where } k = 1, \ldots, N_{div}$$

formed by correlation functions $R_\alpha(t_k)$, where $\alpha = x, y, z$, corresponding to the respective components x, y and z of the measured magnetic field $H_m(r-r_c, \theta_c, t)$. Here, a symbol t_k , contained as a variable of the projective component , indicates that the projective component depends on the variable t_k.

In this method, the vector $e_n(t_k)$ can be used as the direction of the noise magnetic field through utilization of the time t_k . [in which] In this time t_k, a fluctuation in the absolute value of the projective component vector $H_m(r-r_c, \theta_c, t_k, t)$, where $k = 1, \ldots, N_{div}$ --

$$\mathrm{var}(t_k)=\frac{\sqrt{\left\langle\left(\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)-\left\langle\left|\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t\right)^2\right\rangle_t}}{\left\langle\left|\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t},\ k=1,\ \ldots,\ N_{\mathrm{div}}. \quad (56)$$

-- [becomes minimum or] is minimized or becomes smaller than a predetermined value (S145a). In the above , $\langle\cdot\rangle_t$ means the calculation of the time average.

[Further, variances of] In addition, variations in the x-component $H_{m,x}(r-r_c, \theta_c, t_k, t)$, y-component $H_{m,y}(r-r_c, \theta_c, t_k, t)$ and z-component $H_{m,z}(r-r_c, \theta_c, t_k, t)$ of the projective component vector $H_m(r-r_c, \theta_c, t_k, t)$, where $k = 1, \ldots, N_{div}$,

$$\mathrm{var}_\alpha(t_k)=\frac{\sqrt{\left\langle\left(H_{m,\alpha}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)-\left\langle\left|H_{m,\alpha}^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t\right)^2\right\rangle_t}}{\left\langle\left|\mathbf{H}_m^P(\mathbf{r}-\mathbf{r}_c,\ \theta_c,\ t_k,\ t)\right|\right\rangle_t}, \quad (57)$$

$$\alpha=x,\ y,\ z;\ k=1,\ \ldots,\ N_{\mathrm{div}}.$$

are calculated, and the vector $e_n(t_k)$ can be used as the direction of the noise magnetic field [through utilization of] by using the time t_k in which the sum of the above-mentioned [variances] variations

$$\sum_{\alpha=x,y,z} \mathrm{var}_\alpha(t_k) \tag{58}$$

or

$$\sqrt{\sum_{\alpha=x,y,z} \left(\mathrm{var}_\alpha(t_k)\right)^2}. \tag{59}$$

[becomes minimum or] is minimized or becomes smaller than a predetermined value (S145b). [In this case, there is the possibility] Here, it is possible that the correlation functions $R_x(t_k)$, $R_y(t_k)$ and $R_z(t_k)$ at a certain time t_k [have lost] may lose their original signs. Hence, it is necessary to evaluate the fluctuation of the projective component at each time t_k for four combinations $[R_x(t_k), R_y(t_k), R_z(t_k)]$, $[R_x(t_k), R_y(t_k), -R_z(t_k)]$, $[R_x(t_k), -R_y(t_k), R_z(t_k)]$ and $[R_x(t_k), -R_y(t_k), -R_z(t_k)]$.

[Further, the] The period during which the signal magnetic field is OFF can also be easily [be] set (S145c, S145d) based on the sequence $s(t-t_k)$. By applying the same method as the [first one] Method (1) to the magnetic field vector $H_n(r-r_c, \theta_c, t)$ as measured in this period, the direction $e_n(r)$ of the noise magnetic field vector $H_n(r, t)$ can be obtained (S146). [In the above, use is made of the] Here, time t_k of the equally spaced N_{div} sections of [a] the time length T_{div} [divided] derived from the period T_{period} can be used, but it is also possible to use the time [when] at which the correlation function given by Eq. (45) or (46) [becomes maximum] is maximized or when the correlation function [becomes maximum] is maximimized and exceeds a predetermined value.

[(Method for determining the direction of the noise magnetic field when the number of noise magnetic fields is virtually two)]

Determining the direction of the noise magnetic field when the number of such fields is virtually two.

Even in a case of two noise magnetic fields, when a first one of the two noise magnetic fields has [far higher] an intensity far greater than that of the second noise magnetic field at a first frequency _,_ and the second noise magnetic field has [far higher] an intensity far greater than that of the first noise magnetic field at the second frequency, the [directions] direction of the first and second noise magnetic field can easily be calculated through [utilization of] using these frequency components in the measured magnetic field.

If the first or second frequency is close to the frequency of the signal magnetic field, the directions of the noise magnetic fields can be determined from the measured magnetic field [having] that has passed through a band pass filter that permits the passage [therethrough] of only those frequencies near [those] the frequencies of the signal magnetic field, by the same method as [the fourth or fifth method] Methods (4) or (5), [for use in the case] which are used in situations of virtually one noise magnetic field.

When either [of] the first and second frequencies [does] is not equal to the frequency of the signal magnetic field, the [directions] direction of the respective noise magnetic fields [need] needs only [to] be calculated by the [same method as the first one for use] used in Method (1) for situations [in the case] of virtually one noise magnetic field.

[(] Other embodiments [)]

The present invention [is also effective] can also be put to good use when the signal magnetic field generated by the magnetic field source is virtually axially symmetric, and the invention permits the [position] determination of position with [a smaller number of] fewer magnetic sensors or by a magnetic field [sensing] being sensed at [a smaller number of] fewer positions than [in the case of] with a

magnetic field of low symmetry.

Further, there are cases in which [when] only one noise magnetic field affects the measurement of the digging position and the tilt angle of the magnetic field source, which is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, [of the magnetic field source] is known . [which is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction] Here, the projective component of the magnetic field, measured at each of two or more different positions [,] and on a plane perpendicular to the direction of the noise magnetic field sensed at each of the magnetic field sensing positions , is calculated [; the] The position of the magnetic field source and its azimuth angle [that is] (the direction of the axis of symmetry in a horizontal plane) can be calculated from the above [-said] projective component.

[Further,] In addition, according to this [invention] method of the subject invention, when virtually one noise magnetic field affects the measurement of the digging position, one can calculate the projective component of the magnetic field, measured at each of three or more different positions, on a plane perpendicular to the direction of the noise magnetic field sensed at each of the magnetic field sensing positions [is calculated; the] . The position of the magnetic field source, its tilt angle [that is] (an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction), and the azimuth angle of the magnetic field source [that is he] (the direction of the axis of symmetry in the horizontal plane) can be calculated from the [above-] said projective component.

[Further, when] There are situations in which virtually two noise magnetic

fields alone affect the measurement of the digging position and the tilt angle of the magnetic field source [is known] , which is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, is known . Here, the projective component of the magnetic field, measured at [each of] four or more [different] positions, on a straight line perpendicular to both [of] the direction of a first [one] of [the] two noise magnetic fields sensed at each magnetic field sensing position and the direction of the [remaining second] other of the two noise magnetic [field] fields sensed at the same position , can be [is] calculated [;] , and the position of the magnetic field source and its azimuth angle that is the direction of the axis of symmetry in the horizontal plane can be calculated from the above [-said] projective component.

Further, [when] in situations where virtually two noise magnetic fields alone affect the measurement of the digging position, the projective component of the magnetic field, measured at [each of] five or more [different] positions, on a straight line perpendicular to both [of] the direction of the [a] first [one] of [the] two noise magnetic fields sensed at each magnetic field sensing position and the direction of the [remaining second] other noise magnetic field sensed at the same position [is] can be calculated [;] . Here, the position of the magnetic field source, its tilt angle that is an inclination of the axis of symmetry corresponding to the axial direction of the signal magnetic field set in the magnetic field source with respect to the vertical direction, and the azimuth angle that is the direction of the axis of symmetry in the horizontal plane can be calculated from the above [-said] projective component.

Moreover, when virtually two noise magnetic fields alone affect the measurement of the digging position, the frequency component of [a] the first [one] of [the] two noise magnetic fields, [in the vicinity of] near which the remaining second noise magnetic field and the signal magnetic field have substantially no frequency components, is measured in order to [thereby] permit

detection of the direction of the first noise magnetic field in terms of a vector [;] Here, as well, [and] the frequency component of the second noise magnetic fields, [in the vicinity of] near which the first noise magnetic field and the signal magnetic field have substantially no frequency components, is measured in order to [thereby permit detection of] detect the direction of the second noise magnetic field in terms of a vector.

In [the present] this invention, [it is effective to use, as a magnetic sensor,] a three-axis magnetic sensor that senses three magnetic fields orthogonal to one another at substantially the same position is effective as a magnetic sensor.

[The] However, the magnetic sensor [for use] in the present invention may be any [kinds] kind of [sensors] sensor as long as [they are] it is can function in [capable to] three magnetic fields orthogonal to one another at substantially the same position [, but the] . The three-axis magnetic sensor is suitable [which] because it senses three magnetic fields orthogonal to one another at substantially the same position. [Alternatively, it is possible that] In the alternative, one magnetic sensor that is capable of sensing a magnetic field in only one direction [is] can be turned [at] in the same position [toward] to face three different orthogonal directions [one after another] in sequence to sense the three orthogonal magnetic fields.

In [carrying out] employing the present invention, [it is possible to employ such] one can use a frame such as [a] frame 12 [as] depicted in Fig. 32 , which has a magnetic sensor fixing means 11 mounted [thereon] on it so it can [to] fix three-axis magnetic sensors and a tilt angle gauge 13 for detecting the inclination of the frame with respect to a vertical direction. The position of each magnetic sensor fixing means on the frame is known, and the magnetic sensor fixing means acts to fix [possesses a function of fixing] the magnetic sensor in a predetermined orientation to the frame. The magnetic sensor fixing means 11 [is] can be provided with [, for example,] three faces orthogonal to one another, and has a mechanism that fixes the magnetic sensor at a predetermined angle when a

predetermined face of the sensor case is pressed against any [one] of the three faces of the sensor fixing means. One magnetic sensor or one three-axis magnetic sensor is fixed to these magnetic sensor fixing means one after another to sense the magnetic fields.

In another alternative, a plurality of magnetic sensors may be fixed in predetermined orientations to the frame 12 at a plurality of positions to simultaneously sense magnetic fields at [the] this plurality of positions.

As described above, the present invention employs a frame provided with a plurality of magnetic sensor fixing means each capable of removably or fixedly mounting a three-axis magnetic sensor and a tilt angle sensor capable of detecting the tilt angle of an orthogonal coordinate system to the vertical direction [, the] The magnetic fixing means [being] are mounted on the frame so that their positions and orientations are known [;] . And the magnetic sensor is removably or fixedly mounted on a required number of magnetic sensor fixing means to sense magnetic fields, [and] while the tilt angle of the frame during magnetic field sensing and the orientation of the magnetic sensor at each magnetic sensor mounting position [with respect to] toward the frame are used to calculate , from the magnetic field sensed at each magnetic sensor mounting position , the sensed magnetic field, a noise magnetic field and a signal magnetic field as vectors in a coordinate system fixed to the ground.

The magnetic field generating means for the signal magnetic field in the present invention may be a coil. The magnetic field generating means may also be one electric wire [as well], or [may also be] one electric wire that is straight only [in the vicinity of] near the place of [position] the determination of position.

[As described above, even] Even if a buried power line, railroad tracks, or similar noise magnetic sources are present near a construction site, the [present] subject invention [permits] will afford highly reliable [position] determination of position and will not be [without being] affected by the noise magnetic fields generated by such noise magnetic field sources.

The present invention is intended for measuring the digging position in the non-open-cut method of excavation, but is applicable as well to many technical fields that [involve] determine position [determination] by means of sensing magnetic fields.